

Extrusion of Cross-Linked Hydroxypropylated Corn Starches

I. Pasting Properties¹

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ABSTRACT

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A series of cross-linked (0, 0.014, 0.018, 0.024, and 0.028% POCl₃, dry starch basis) hydroxypropylated (8%) corn starches were extruded using a Leistritz micro-18 co-rotating extruder. Process variables included moisture, barrel temperature, and screw design. Differential scanning calorimetry and X-ray diffraction studies showed the level of starch crystallinity decreased with increasing severity of extrusion conditions. Pasting properties of the extruded starches were examined using a Rapid

Visco Analyser. Pasting profiles of starches extruded at different conditions displayed different hot paste viscosity and final viscosity. Increasing starch moisture content during extrusion and level of cross-linking increased starch viscosity ($P < 0.0001$), whereas increasing extrusion temperature and shear decreased starch viscosity ($P < 0.0001$). Interactions were found between level of cross-linking and screw design and between extrusion temperature and starch moisture content ($P < 0.0001$).

Extrusion is an important method for processing starch and starch-based products (Colonna et al 1984, Colonna et al 1989, Harper 1989). Extrusion cooking has been studied for the production of pregelatinized, unmodified starches (Anderson et al 1970, Mercier and Feillet 1975, Mercier 1977, Gomez and Aguilera 1984, Doublier et al 1986, Chinnaswamy and Hanna, 1990, Ryu and Walker 1995). Traditionally, pregelatinized starches have been produced by drum drying (Powell 1967). Pregelatinized starches display an instant viscosity on dispersion in water without heating, and their properties are dependent on cooking and drying conditions (Colonna et al 1984)

The characteristics of extruded native starches are well documented, whereas relatively little is known of extruded chemically modified starches. Extrusion processing is used to produce pregelatinized starches, which have been reported to display different pasting properties from those produced via conventional cooking and drum drying (Colonna et al 1984, Pan et al 1998). The differences are attributed to varying degrees of depolymerization and molecular entanglement resulting from extrusion (Colonna et al 1984, Diosady 1986, Harper 1992). Extruded starches have been characterized using differential scanning calorimetry (DSC), intrinsic viscosity, pasting profiles, and chromatography. When large numbers of samples are generated, however, a rapid method of analysis, such as a Rapid Visco Analyser (RVA) pasting profile, is advantageous and has been used for starch mixtures and extruded starches (Walker et al 1988, Deffenbaugh and Walker 1989, Deffenbaugh and Walker 1990, Harper 1992, Whalen et al 1997).

The objectives of this study were to characterize a series of hydroxypropylated (8%) and cross-linked (0.0, 0.014, 0.018, 0.024, 0.028% POCl₃) normal corn starches extruded at different conditions using DSC, X-ray diffraction, and RVA pasting profiles. Extrusion variables included screw design of the extruder, starch moisture content, extrusion temperature, and level of starch cross-linking.

MATERIALS AND METHODS

Materials

Normal corn starch was obtained from the Grain Processing Corporation, Muscatine, IA. Chemicals used were reagent-grade. Propylene oxide, was obtained from Dow Chemical Co. (Midland,

MI); phosphorous oxychloride was obtained from FMC (Princeton, NJ). Other chemicals were used as received without further treatments.

Chemical Modifications of Starch

Hydroxypropylation. An aqueous slurry of unmodified dent corn starch (40.0%, w/w) was heated to 40–50°C with agitation and purged with nitrogen gas. Sodium hydroxide (1.6%, dsb) and sodium chloride (24%, dsb) and sodium sulfate (2%, dsb) were added to the slurry under vigorous agitation followed by the addition of propylene oxide (8%, dsb). The reaction was allowed to proceed at 43°C for 16 hr until terminated by adjustment to pH 6.0 (Hjermstad 1967, Tuschoff 1986, Rutenberg and Solarek 1984).

Cross-linking. NaOH (0.5–1.0%, dsb) and phosphorous oxychloride were slowly added (0.01–0.03%, dsb) to the agitated slurry (Hullinger 1967, Rutenberg and Solarek 1984, Solarek 1986), and the reaction was run at 43°C for 2 hr. The reaction was terminated by adjusting to pH 5.0–6.0 using hydrochloric acid. After pH adjustment, the reaction slurry was thoroughly washed to remove salts and reaction by-products and dried at 40°C for 12 hr.

Starch Extrusion

Starch extrusion was carried out using a co-rotating extruder (Leistritz Micro-18, American Leistritz Extruder Co., Somerville, NY) with a 30:1 screw length to diameter ratio and a 3.175 mm die opening. Extruder screws were designed with an increasing number of kneading blocks to impart increasing shear to the extrudates (Fig. 1). The extruder barrel was composed of six programmable heating zones (Table I). Starches with varying moisture contents were prepared using a mixer (Kitchen Aid, St. Joseph, MI) and a spray bottle to add water on a weight basis. Mixtures were sealed in polyethylene bags and allowed to equilibrate for at least 2 hr before extrusion. Starch was fed into the extruder at a rate of 1.6 kg/hr. Mean residence time in the extruder barrels using dyed starch was 49, 56, and 68 sec, respectively, for the low-, medium-, and high-shear screw designs shown in Fig. 1.

Extruded starch was collected as a continuous strand after torque, barrel temperature, and die pressure reached a steady state. On completion of extrusion, the extrudate strands were immediately placed in a 100°C forced-air oven and dried for 8 hr. Dried extrudates were milled with a hammer mill followed by a cyclone mill (Udy Corp., Ft. Collins, CO) and then were sieved through a 160-mesh screen. Sieved starches were sealed in polyethylene bags and stored until analysis.

Experimental Design

The treatment design was four factorial with a total of 162 treatments. Two replicates of the 162 treatments were carried out. Variables and their levels used as treatments are presented in

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Table I. The experiment was conducted following a split-split plot design. Split plot treatments were the moisture and temperature combinations. Screw designs were randomly set at low, medium, or high, and the starches were extruded in random order. A single experimental error term was used because the three error terms in the split-split plot analysis of the hot paste viscosity and final viscosity were similar.

Thermal Properties of Starches Determined by DSC

Thermal properties of the starches were analyzed by using differential scanning calorimeter (DSC-7, Perkin Elmer Corp., Norwalk, CT) equipped with an Intracooler II System and Pyris thermal analysis software (Perkin-Elmer). Starch and water mixtures (1:3, w/w) were sealed in aluminum pans and equilibrated at room temperature for 2 hr before analysis. An empty aluminum pan was used as the reference. The samples were heated at 10°C/min over a temperature range of 25–100°C. Indium and zinc were used as reference standards. The gelatinization temperature and enthalpy change were determined following the procedure of Kasemsuwan et al (1995). Enthalpy change (ΔH), onset temperature (T_o), peak temperature (T_p), and conclusion temperature (T_c) were computed.

X-ray Diffraction Patterns

The X-ray patterns of the starches were obtained with copper, nickel foil filtered, $K\alpha$ radiation using a diffractometer (D-500 Siemens, Madison, WI) following the method of Jane et al (1997). The diffractometer was operated at 27 mA and 50 kV. The scanning region of the diffraction angle (2θ) was 4–40° at a 0.05° step size with a count time of 2 sec. Starches were equilibrated at 100% rh for 24 hr at 25°C before examination.

Pasting Properties of Extruded Starches

Pasting profiles of extruded starches were examined using a Rapid Visco Analyser (RVA-4, Newport Scientific, NSW, Australia). Starch suspension (15%, dsb) was prepared by weighing milled, extruded starch (4.50 g, dsb) into an RVA canister and

adjusting the total weight to 30 g with distilled water. A manual premixing step with a spatula was required for the pregelatinized starch samples to ensure homogeneity of the sample mixture. After premixing, the starch paste was removed from the spatula with the RVA paddle. The heating profile was hold at 30°C for 1 min, heat to 95°C at 6.5°C/min, hold at 95°C for 5.5 min, cool to 50°C at 6°C/min, and hold at 50°C for 2 min. Paddle speed was set at 960 rpm for the first 5 sec and then 160 rpm for the remainder of the analysis. Viscosity values were collected after holding at 95°C, at 16 min (hot paste), and cooling to 50°C, at 26 min (final).

RESULTS AND DISCUSSION

Thermal Properties

The onset gelatinization temperature and enthalpy change of native corn starch determined by DSC were 66.1°C and 13.2 J/g, respectively. The hydroxypropylated (8%) maize starches with

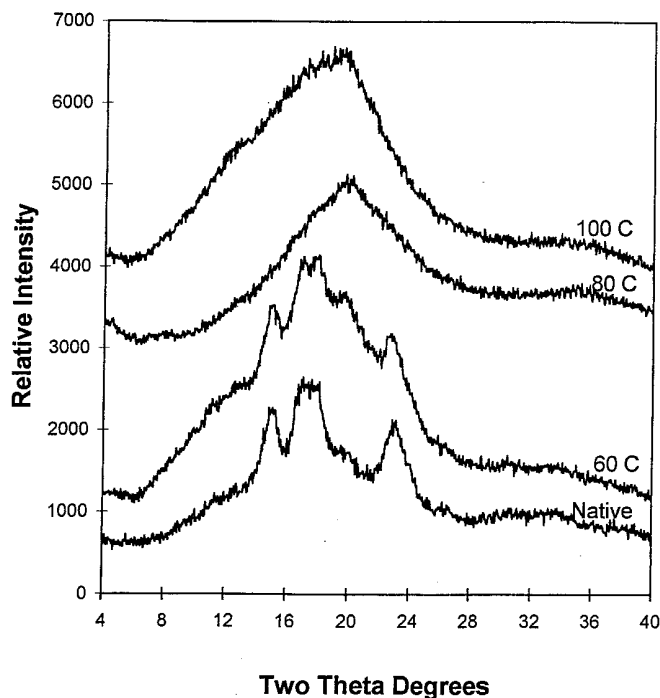


Fig. 2. X-ray diffraction patterns for native corn starch and native corn starch extruded at 30% moisture and high shear at 60, 80, and 100°C.

TABLE I
Experimental Variables and Levels of Use

Factor	Factor Levels				
Cross-linking (%POCl ₃)	0	0.014	0.018	0.024	0.028
Moisture (% dsb)	30	35	40		
Screw	Low	Medium	High		
Temp. profile (feed → die) of barrel (°C)	40, 45, 50, 55, 60, 60	45, 55, 65, 75, 80, 80	60, 70, 80, 90, 100, 100		

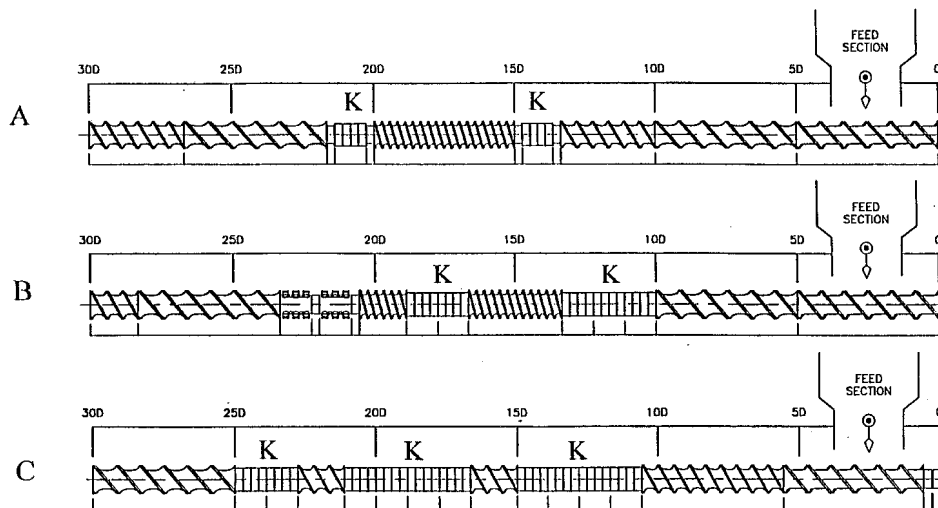


Fig. 1. Screw designs. Number of kneading elements increase from low (A), medium (B), to high (C) shear. K denotes sections of kneading blocks.

cross-linking levels of 0, 0.014, 0.018, 0.024, and 0.028% POCl₃, had onset gelatinization temperatures of 50.6, 52.6, 50.6, 51.9, and 50.8°C, and enthalpy changes of 6.5, 9.2, 8.5, 8.1, and 8.3 J/g, respectively (Table II). The decreased gelatinization temperatures and enthalpy changes of the chemically modified starches from that of the native corn starch indicated the crystalline structure of the native starch granules was destabilized and possibly reduced during the cross-linking and hydroxypropylation reactions at alkaline pH (Table II). DSC thermograms of extruded starches showed those extruded at 60 and 80°C displayed a smaller gelatinization endotherm than their respective unextruded counterparts. The onset gelatinization temperatures of the extruded starches generally were somewhat higher than those of the parent starches (Table II). The magnitude of the enthalpy change decreased when the extrusion temperature increased. Increased onset gelatinization temperatures of the extruded starches indicated that starch granules with lower gelatinization temperatures (such as damaged starches) were gelatinized during extrusion; those with higher gelatinization temperatures were more resistant to extrusion. Starches

subjected to higher extrusion temperatures (100°C) showed no gelatinization peak, indicating total gelatinization of the starch during high-temperature extrusion.

Starch Crystallinity

The X-ray diffraction patterns of the extruded starches showed that crystallinity decreased as the temperature of extrusion increased. Native corn starch displayed an A-type X-ray diffraction pattern (Fig. 2). Native corn starch extruded at 30% moisture and high shear at 60°C displayed reduced crystallinity. At extrusion temperatures of 80 and 100°C, the starch was gelatinized as indicated by the absence of crystalline peaks (Fig. 2). X-ray diffraction patterns of extruded hydroxypropylated and cross-linked hydroxypropylated starches showed similar decreases in crystallinity as extrusion temperature increased (data not shown). DSC showed a small thermal transition peak for the native corn starch extruded at 80°C, whereas X-ray analysis showed no diffraction pattern. It is possible that the remaining crystallites were too small to display an X-ray diffraction pattern. The X-ray pattern of the native corn

TABLE II
Thermal Properties of Starch Gelatinization of Native Starches and Selected Extruded Starches by Differential Scanning Calorimetry^a

Starch ^b	Moisture Content (%)	Temperature (°C)	Screw Shear	Onset (T _o)	Peak (T _p)	Conclusion (T _c)	Enthalpy (ΔH)
Native				66.1 ± 0.3 ^c	70.7 ± 0.2	75.2 ± 0.3	13.2 ± 0.8
HP, 0.0% POCl ₃				50.6 ± 0.1	55.6 ± 0.1	62.0 ± 0.2	6.5 ± 0.6
HP, 0.014% POCl ₃				52.6 ± 0.1	57.4 ± 0.2	63.3 ± 0.1	9.2 ± 0.9
HP, 0.018% POCl ₃				50.6 ± 0.2	56.0 ± 0.1	62.0 ± 0.3	8.5 ± 0.4
HP, 0.024% POCl ₃				51.9 ± 0.0	57.2 ± 0.0	63.3 ± 0.0	8.1 ± 0.1
HP, 0.028% POCl ₃				50.9 ± 0.3	56.5 ± 0.3	62.8 ± 0.1	8.3 ± 0.3
Native	30	60	Low	69.8 ± 0.1	73.7 ± 0.2	77.3 ± 0.5	1.9 ± 0.0
	30	80	Low	66.4 ± 0.0	70.7 ± 0.0	73.6 ± 0.1	0.4 ± 0.0
	30	100	Low	nd ^d			
	30	60	Med	63.2 ± 0.1	69.3 ± 0.0	74.3 ± 0.3	2.0 ± 0.3
	30	80	Med	67.9 ± 0.2	72.3 ± 0.2	76.2 ± 0.1	1.4 ± 0.1
	30	100	Med	nd			
	30	60	High	65.5 ± 0.1	70.4 ± 0.5	74.5 ± 0.0	0.9 ± 0.2
	30	80	High	66.7 ± 0.4	71.6 ± 0.2	75.6 ± 0.0	1.6 ± 0.2
	30	100	High	nd			
	40	60	Low	68.2 ± 0.3	72.2 ± 0.2	76.2 ± 0.4	4.3 ± 0.2
	40	80	Low	73.3 ± 0.4	76.9 ± 0.4	80.3 ± 0.3	0.6 ± 0.1
	40	100	Low	nd			
	40	60	High	65.2 ± 0.1	69.8 ± 0.2	74.0 ± 0.3	5.3 ± 0.2
	40	80	High	71.0 ± 0.2	74.2 ± 0.2	77.5 ± 0.2	0.9 ± 0.4
	40	100	High	nd			
HP, 0.0% POCl ₃	30	60	Low	52.9 ± 0.4	58.1 ± 0.4	65.0 ± 0.5	0.9 ± 0.1
	30	80	Low	66.4 ± 0.1	70.7 ± 0.2	73.6 ± 0.1	0.4 ± 0.1
	30	100	Low	nd			
	30	60	High	51.0 ± 0.1	56.5 ± 0.2	63.5 ± 0.7	1.7 ± 0.1
	30	80	High	nd			
	40	60	Low	55.6 ± 0.0	60.0 ± 0.2	64.4 ± 0.7	0.3 ± 0.1
	40	80	Low	nd			
	40	60	High	51.2 ± 0.0	56.5 ± 0.2	63.4 ± 0.8	1.7 ± 0.0
	40	80	High	61.8 ± 0.9	65.1 ± 0.6	66.7 ± 0.9	0.4 ± 0.2
	40	100	High	nd			
HP, 0.028% POCl ₃	30	60	Low	54.4 ± 0.2	59.4 ± 0.6	64.2 ± 0.0	0.5 ± 0.0
	30	80	Low	59.3 ± .0	60.8 ± 0.1	63.2 ± 0.1	0.2 ± 0.0
	30	100	Low	nd			
	30	60	Med	50.3 ± 0.6	56.1 ± 0.1	58.8 ± 0.0	0.2 ± 0.0
	30	80	Med	nd			
	30	60	High	66.9 ± 0.6	69.0 ± 0.9	71.2 ± 0.3	0.3 ± 0.1
	30	80	High	nd			
	35	60	High	50.7 ± 0.2	56.3 ± 0.1	62.2 ± 0.3	0.9 ± 0.1
	35	80	High	nd			
	40	60	Low	54.7 ± 0.2	60.3 ± 0.7	65.0 ± 0.9	0.5 ± 0.0
	40	80	Low	nd			
	40	60	High	52.5 ± 0.1	57.3 ± 0.0	62.8 ± 0.1	1.8 ± 0.2
	40	80	High	nd			

^a Results are the mean of at least three replicates.

^b HP = hydroxypropylated.

^c ± Standard deviation.

^d No peak was detected

starch extruded at 100°C displayed a peak at ≈20° and small bumps at 13°, indicating a small amount of V-type amylose-lipid complexes.

Pasting Properties

The pasting profiles of the native and chemically modified starches (8%, dsb) are shown in Fig. 3. The starch pasting temperatures were 76.4, 57.3, 59.1, 59.0, 59.5, and 59.9°C for native corn starch and cross-linked (0.0, 0.014, 0.018, 0.024, and 0.028% POCl₃) hydroxypropylated (8%) corn starches, respectively (Fig. 3). The pasting temperatures of the modified starches increased by cross-linking. The final viscosity of the starches increased with increasing levels of cross-linking, 131.7, 253.8, 307.4, 325.8, and 380.4 RVU, for cross-linked (0.0, 0.014, 0.018, 0.024, and 0.028% POCl₃) hydroxypropylated (8%) corn starches, respectively, compared with 214.8 RVU for native starch (Fig. 3). The pasting peak viscosity increased with levels of cross-linking up to 0.018% POCl₃. With further increases in cross-linking level in normal starches, the peak viscosity decreased and the final viscosity increased (Fig. 3), which agreed with those reported by Rutenberg and Solarek (1984) and Kasemsuwan and Jane (1994).

The experimental design for extrusion processing consisted of two replicates of 162 treatment combinations that included screw design (shear), extrusion temperature, starch cross-linking level, and starch moisture content. Pasting profiles were generated and analyzed for all treatment combinations. Because the extruded starches displayed low hot paste viscosity and final viscosity, a solid content of 15% (dsb) was used for the pasting study, which resulted in reproducible RVA pasting profiles with adequate viscosity levels for detection. Most of the extruded starches displayed substantial instant viscosity after stirring for 1 min at 30°C, indicating that the starches had been pregelatinized by extrusion (Figs. 3–7).

Average hot paste viscosity and final viscosity of extruded starches were calculated for each of the treatments and are summarized in Tables III and IV. Differences between the means of the treatments are discussed in terms of significant variables and variable interactions. Extruded starches displayed different pasting profiles from their respective parent starches (Figs. 3–7). Representative pasting profiles of extruded starches from various treatment combinations are shown in Figs. 4–7.

TABLE III
Average Viscosities (RVU)^a for Combinations of Starch Moisture Content and Extrusion Temperature (standard error = 12.93)

Starch Moisture Content (%)	Extrusion Temperature (°C)			Starch Moisture Content Mean ^b
	60	80	100	
30	94.61	102.08	104.71	100.20
35	170.35	160.01	133.79	154.71
40	267.32	230.42	198.59	232.11
Extrusion temp. mean ^c	177.43	164.14	145.46	

^a Rapid Visco Analyser units.

^b Standard error of the starch moisture content means = 7.46.

^c Standard error of the extrusion temperature means = 7.46.

TABLE IV
Average Viscosities (RVU)^a for Combinations of Starch Cross-Linking and Shear (standard error = 5.08)

Shear	% POCl ₃ in Cross-Linked and Hydroxypropylated (8%) Corn Starches							Shear Mean ^b
	Native Corn Starch	0	0.014	0.018	0.024	0.028		
Low	347.24	89.95	167.31	226.52	230.61	299.91	226.92	
Medium	292.14	72.3	97.23	120.51	130.19	174.19	147.76	
High	260.77	56.08	80.23	96.68	101.91	135.69	121.89	
Starch cross-linking mean ^c	300.05	72.78	114.92	147.90	154.24	203.26		

^a Rapid Visco Analyser units.

^b Standard error of shear means = 2.28.

^c Standard error of starch cross-linking means = 2.93.

Effect of extrusion temperature. The extrusion temperature affected the hot paste viscosity and final viscosity of extruded starches (Table III). Figure 4 shows cross-linked (0.028% POCl₃) hydroxypropylated (8%) corn starches extruded at 40% moisture, high shear, and increasing temperature (60, 80, and 100°C). Starches extruded at low temperature (60°C) displayed a lower instant viscosity and higher hot paste and final viscosity than those extruded at 80 and 100°C. Similar extrusion temperature effects on instant and final viscosities have been reported for wheat flour (Seiler et al 1980) and wheat starch (Colonna et al 1984). Cross-linked (0.028% POCl₃) hydroxypropylated (8%) corn starch extruded at low temperature (60°C) and high moisture (40%) displayed a small pasting peak with a pasting temperature of 60°C (Fig. 4). This small pasting peak occurred at a similar temperature range to the pasting peak of the unextruded parent starch (Fig. 3). Those extruded starches displaying a small pasting peak also displayed a DSC gelatinization peak with a reduced enthalpy change and residual A-type X-ray diffraction pattern. These results confirmed the presence of remaining crystalline structure in the starches extruded at low temperature (60°C) and were in agreement with the scanning electron microscopy results, which showed distorted and fractured granule residues present in these starches (McPherson and Jane 2000).

Viscosity of extruded starches decreased as temperature of extrusion increased from 60 to 100°C (Table III) ($P < 0.0001$) except for those extruded at 30% moisture content. The increased extrusion temperature gelatinized the starches to a greater extent. Passage of the gelatinized starch through the extruder barrel resulted in shear degradation of the molecules and subsequent decreases in hot paste and final viscosity (Bhattacharya and Hanna 1987).

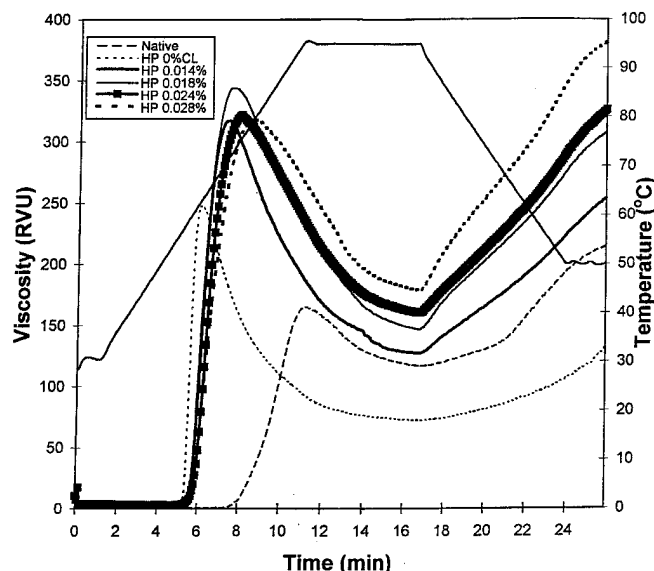


Fig. 3. Rapid Visco Analyser pasting profiles of unextruded native corn and cross-linked (0, 0.014, 0.018, 0.024, and 0.028% POCl₃) hydroxypropylated (8%) corn starches at 8% solids (dsb).

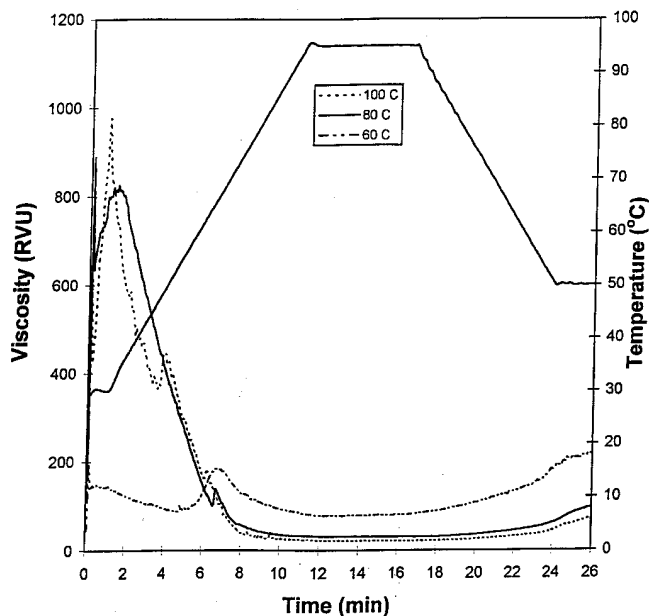


Fig. 4. Rapid Visco Analyser pasting profiles (15% solids, dsb) of cross-linked (0.028% POCl_3) hydroxypropylated (8%) corn starch extruded at 40% moisture and high shear at 60, 80, and 100°C.

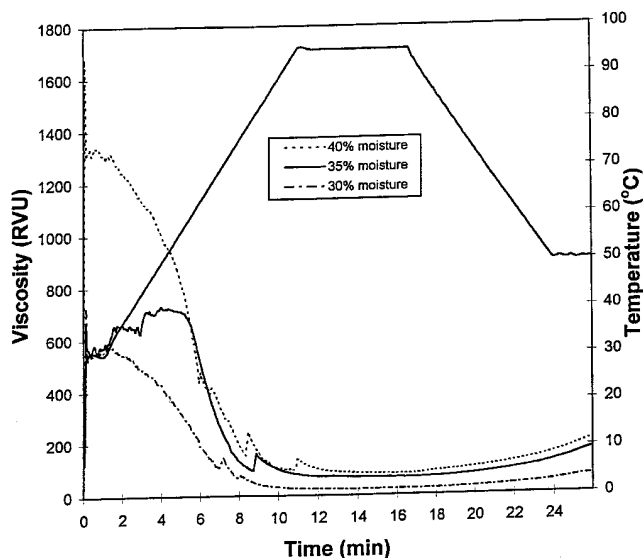


Fig. 5. Rapid Visco Analyser pasting profiles (15% solids, dsb) of cross-linked (0.014% POCl_3) hydroxypropylated (8%) corn starch extruded at 100°C and medium shear at 30, 35, and 40% moisture.

Effect of moisture content. Viscosity of the extruded starches increased as starch moisture content increased from 30 to 40% (Table III) ($P < 0.0001$). An example of the effect of varying moisture content during extrusion on starch pasting profiles is shown in Fig. 5 with cross-linked (0.014% POCl_3) hydroxypropylated (8%) corn starch extruded at 100°C and medium shear with moisture levels of 30, 35, and 40%. Moisture acts as a plasticizer during extrusion of starches and lowers the extent of shear degradation (Lai and Kokini 1991). This effect has been reported for hot paste and final viscosity in unmodified wheat starch (Colonna et al 1984, Mason and Hosney 1986) and corn starch (Chinnaswamy and Hanna 1990). Amylopectin molecular weights of extruded cross-linked hydroxypropylated (8%) starches decreased as the moisture content decreased during extrusion (McPherson and Jane 2000). Starch extruded with 30% moisture content displayed a slight increase in viscosity with increasing temperature from 60 to 80°C and remained unchanged from 80 to 100°C, which differed

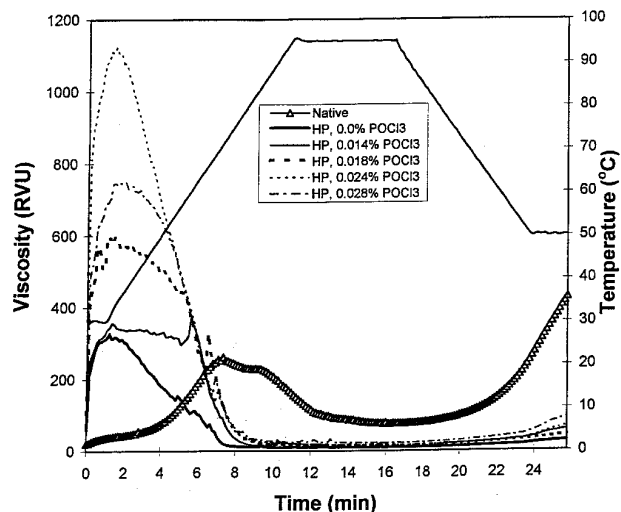


Fig. 6. Rapid Visco Analyser pasting profiles (15% solids, dsb) of native corn and cross-linked (0, 0.014, 0.018, 0.024, and 0.028% POCl_3) hydroxypropylated (8%) corn starch at 30% moisture, 100°C, and high shear.

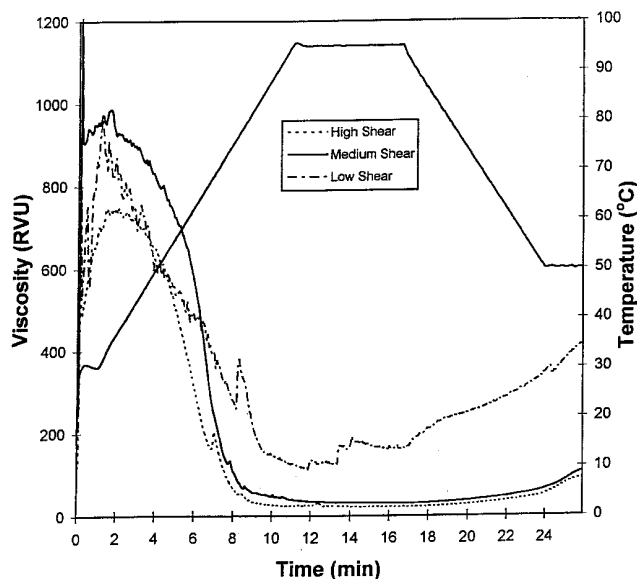


Fig. 7. Rapid Visco Analyser pasting profiles (15% solids, dsb) of cross-linked (0.028% POCl_3) hydroxypropylated (8%) corn starch extruded at 100°C, 30% moisture at low, medium, and high shear.

from those extruded with 35 and 40% moisture ($P < 0.0001$) (Table III). This difference may be attributed to the starch with lower moisture content having a higher glass transition temperature. Thus, being extruded at higher temperature, the starch became rubbery and resulted in less friction and less degradation as supported by SEM structures and increased glass transition temperatures of cross-linked starches reported by McPherson and Jane (2000).

Effect of cross-linking. As the level of starch cross-linking increased, the average viscosity of the chemically modified starches increased to a greater degree with extrusion at low shear than with extrusion at medium and high shear (Table IV) ($P < 0.0001$). In general, the instant and final viscosity of starch pastes increased with increasing levels of starch cross-linking as shown in Fig. 6 for starches extruded at 30% moisture, 100°C, and high shear. Cross-linked starches retained more structure when extruded at low shear, which resulted in greater hot paste and final viscosity than did those extruded at medium and high shear. The extruded native corn starches had higher average viscosity than did the extruded

chemically modified starches (Table IV). This was caused by the retention of crystalline material in the native starch as shown by DSC, X-ray diffraction, and RVA pasting profiles, which was a result of native corn starch having a higher gelatinization temperature (Table II). Level of starch cross-linking had a significant effect on the viscosity of the extruded starches ($P < 0.0001$). As the level of starch cross-linking increased from 0.0% POCl₃ to 0.028% POCl₃ the average viscosities of the starches also increased (Table IV) ($P < 0.0001$). This is in agreement with the results reported by McPherson and Jane (2000) showing that amylopectin molecular weights of extruded hydroxypropylated (8%) starches with cross-linking were higher than those without cross-linking. Cross-linking is used to impart shear, acid, and thermal stability to starches in various conventional processing applications such as retorting, continuous mixing, and pumping (Hullinger 1967, Rutenberg and Solarek 1984).

Effect of shear. Viscosity of extruded starches decreased as the level of shear increased from low to high (Table IV) ($P < 0.0001$). Figure 7 shows an example of the effect of shear on cross-linked (0.028% POCl₃) hydroxypropylated (8%) corn starch extruded at 100°C and 30% moisture. Similar findings have been reported for extruded corn grits (Barres et al 1990) and wheat flour (Seiler et al 1980).

CONCLUSIONS

Extrusion of hydroxypropylated (8%) corn starch with varying levels of cross-linking (0, 0.014, 0.018, 0.024, and 0.028% POCl₃) at different levels of moisture, barrel temperature, and shear resulted in a range of partially to totally pregelatinized starches. Differential scanning calorimetry and X-ray diffraction both showed remaining crystallinity in starches extruded at low temperature (60°C). Starch moisture content, extrusion temperature, level of starch cross-linking, and screw design were shown to affect pasting characteristics as measured by RVA ($P < 0.0001$). Increasing the starch moisture content level and cross-linking resulted in extruded starches with increased hot paste and final viscosity. The interactions between cross-linking level and level of shear and between starch moisture content and extrusion temperature were significant.

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